

Production of Kaon and Λ in nucleus-nucleus collisions at ultra-relativistic energy from a blast wave model

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The particle production of Kaon and Λ are studied in nucleus-nucleus collisions at relativistic energy based on a chemical equilibrium blast-wave model. The transverse momentum spectra of Kaon and Λ at the kinetic freeze-out stage from our model are in good agreement with the experimental results. The kinetic freeze-out parameters of temperature (T_{kin}) and radial flow parameter ρ_0 are presented for the FOPI, RHIC and LHC energies. And the resonance decay effect is also discussed. The systematic study for beam energy dependence of the strangeness particle production will help us to better understand the properties of the matter created in heavy-ion collisions at the kinetic freeze-out stage.

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I. INTRODUCTION

Study for Quark-Gluon Plasma (QGP) [1] by Ultra-relativistic heavy-ion collisions [2–5] provides an opportunity to understand the production mechanism of strangeness hadrons and the phase space evolution in the system created, especially the energy dependence is thought as one of important observables to study various aspects of the QCD phase diagram [6–8] in the beam energy scan program at RHIC [9]. The s-quarks in strangeness hadrons can be a good probe to investigate the properties of the high dense and temperature matter because there should be no net strangeness content in the colliding system [10–13]. The s-quarks are all created in the reaction. Kaon is produced associated with Λ -hyperon at FOPI energy, and at higher energies, such as in the RHIC or LHC region, it can be produced by another mechanism, the so-called pair production [2–5]. The transverse momentum p_T distribution encodes rich physics information. It has been measured in $p + p$, $p + \text{nuclues}$ or nucleus + nucleus collisions at different energy range by the FOPI [14] and KaoS [15] collaboration at $\sqrt{s_{NN}} = 2.6$ GeV, by the RHIC-STAR collaboration at $\sqrt{s_{NN}} = 62$ GeV [16, 17] and 200 GeV [18, 19] and by the LHC-ALICE collaboration [20–23] at $\sqrt{s_{NN}} = 2.76$ and 7 TeV etc. The resonance decay effect is also discussed in the above papers [16, 24]. Through fitting the measured transverse momentum p_T distribution by a blast wave model [25], one can investigate the properties of the collision system at kinetic freeze-out stage. The temperature T_{kin} parameter and the radial flow at kinetic freeze-out stage can provide some information about the evolution of the expanding phase space. One can also study if the system has reached kinetic equilibrium stage when the hadron interactions completed. The resonances

decay will change the production rate and the p_T distribution of Kaon and Λ . However, it is difficult to estimate the effect quantitatively in experiment. The blast wave model has been applied in experimental analysis [16, 26] to study the kinetic freeze-out properties. Retière and Lisa [27] have explored in detail an analytic parameterization of the freeze-out configuration and investigated the spectra, the collective flow, and the HBT correlation of the hadrons produced in head-on nuclear collisions at top RHIC energy. In addition, the DRAGON [28] and the THERMINATOR2 [29, 30] models have been developed to study the phase-space distribution of produced hadrons at freeze-out stage. In this paper, we carry out a detailed study on the beam energy dependence of Kaon and Λ production based on a blast-wave model. The transverse momentum distributions of Kaon and Λ are presented. The chemical and kinetic freeze-out parameters are consistent with the ones extracted from experimental data. The resonance decay effect is also investigated and an approximate estimation of the percent of Kaon and Λ from resonance decay to total Kaon and Λ is achieved.

II. BLAST-WAVE MODEL WITH THERMAL EQUILIBRIUM MECHANISM

As discussed above, within the framework of the blast-wave model, the fireball created in high-energy heavy-ion collisions is assumed to be in local thermal equilibrium and expands at a four-component velocity u_μ . The phase-space distribution of hadrons emitted from the expanding fireball can be expressed as a Wigner function [27–30]

$$S(x, p)d^4x = \frac{2s+1}{(2\pi)^3} m_t \cosh(y-\eta) \exp\left(-\frac{p^\mu u_\mu}{T_{kin}}\right) \Theta(1-\tilde{r}(r, \phi)) H(\eta) \delta(\tau-\tau_0) d\tau \tau d\eta r dr d\phi, \quad (1)$$

where s , y , and m_t are the spin, rapidity, and transverse mass of the hadron, respectively, and p_μ is the four-component momentum. Equation (1) is formulated in a Lorentz covariant way, r and ϕ are the polar coordinates, and η and τ are the pseudorapidity and the proper time, respectively. \tilde{r} is defined as

$$\tilde{r} = \sqrt{\frac{(x^1)^2}{R^2} + \frac{(x^2)^2}{R^2}}, \quad (2)$$

with (x^1, x^2) standing for the coordinates in the transverse plane and R being the average transverse radius. The kinetic freeze-out temperature T_{kin} and the radial

flow parameter ρ_0 are important in determining the transverse momentum spectrum. And the latter will affect the four-component velocity field. Since we are currently interested in the p_T spectrum at mid-rapidity, the pseudorapidity distribution $H(\eta)$ is not important. The p_T spectrum can then be written as

$$\frac{dN}{2\pi p_T dp_T} = \int S(x, p) d^4x. \quad (3)$$

A thermal equilibrium model is employed to calculate the chemical components of hadrons. The particle density of species i can be expressed as [28, 31–36]

$$\begin{aligned} n_i(T_{ch}, \mu_B, \mu_S) &= g_i \int \frac{d^3p}{(2\pi)^3} \left[\exp\left(\frac{\sqrt{p^2 + m_i^2} - (\mu_B B_i + \mu_S S_i)}{T_{ch}}\right) \mp 1 \right]^{-1} \\ &= I\left(g_i, \frac{m_i}{T_{ch}}\right) \sum_{n=1} (\pm 1)^{n+1} \exp\left(n \frac{(\mu_B B_i + \mu_S S_i)}{T_{ch}}\right), \\ I\left(g_i, \frac{m_i}{T_{ch}}\right) &= g_i \int \frac{d^3p}{(2\pi)^3} \left[\sum_{n=1} (\pm 1)^{n+1} \exp\left(-n \frac{\sqrt{p^2 + m_i^2}}{T_{ch}}\right) \right], \end{aligned} \quad (4)$$

with the upper (lower) sign for bosons (fermions) and g_i being the degeneracy factor. Assuming that the chemical equilibrium condition is satisfied, Eq. (4) essentially determines the fraction of particle species i . The particle yield can be described by adjusting parameters such as the chemical freeze-out temperature T_{ch} , the baryon chemical potential μ_B , the strangeness chemical potential μ_S , and the system volume V . And then the fraction of particle species i and its phase-space distribution can be calculated from Eqs. (4) and (3).

III. RESULTS AND DISCUSSION

The rapidity distribution of K^+ , proton and Λ are presented in figure 1. The hadron rapidity distribution is related to the density at reaction scope. The calculated results can describe the data from the FOPI [14] and KaoS collaborations [15] for K^+ , proton and Λ in Ni+Ni collisions at $\sqrt{s_{NN}} \simeq 2.6$ GeV. The Λ is mainly produced at midrapidity ($-0.5 < y < 0.5$) and different from proton distribution at forward/backward rapidity. This results from the pronounced longitudinal expansion of proton

and indicates large degree of transparency in Ni + Ni system at the FOPI energies [14]. A similar calculation for dN/dy from other groups can be found in Ref. [37] and our previous results for Λ were calculated by a transport model [38].

The collective properties of the hot and dense matter created in ultra-relativistic heavy-ion collisions at freeze-out stage can be studied through transverse momentum (p_T) distributions of identified particles. The radial flow

$$\langle \beta \rangle = \int \operatorname{arctanh}\left(\rho_0 \frac{r}{R}\right) r dr / \int r dr \quad (5)$$

is related to the maximum flow rapidity

$$\rho = \tilde{r} [\rho_0 + \rho_a \cos(2\phi)]. \quad (6)$$

The results are independent of ρ_a since the ϕ dependence is averaged out after integration.

Transverse momentum (p_T) spectrum is a basic observable in Ultra-relativistic heavy-ion collisions [39, 40]. By fitting the transverse momentum spectra with thermal model, information of the system created in the collisions can be obtained, such as the kinetic freeze-out temperature and the radial flow. If the spectra are identified

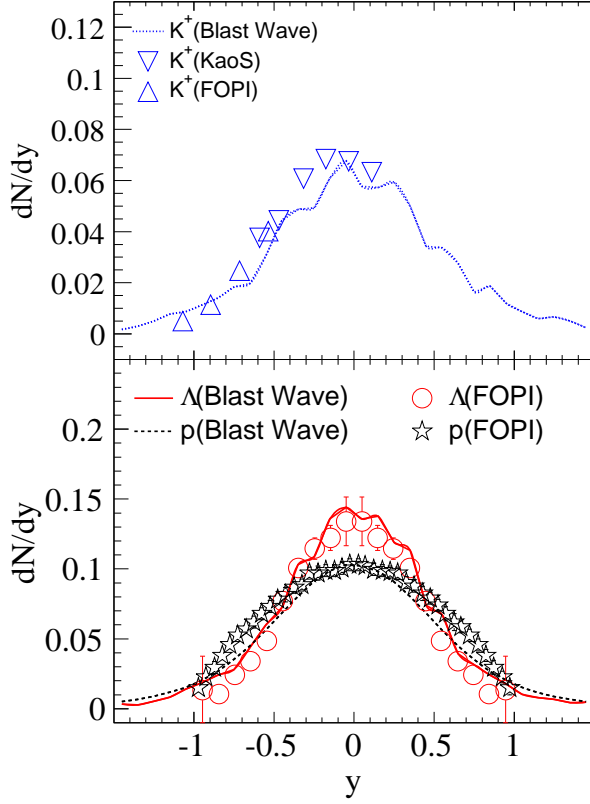


FIG. 1: (Color online) Rapidity distribution of K^+ , Λ and proton (normalized to Λ yield) in Ni + Ni central collisions at $\sqrt{s_{NN}} = 2.6$ GeV. Lines represent the model calculations with $T_{kin} = 30$ MeV, $\rho_0 = 0.6$, $T_{ch} = 49$ MeV and $\mu_B = 815$ MeV; Symbols are data from the FOPI [14] and KaoS [15] experiments.

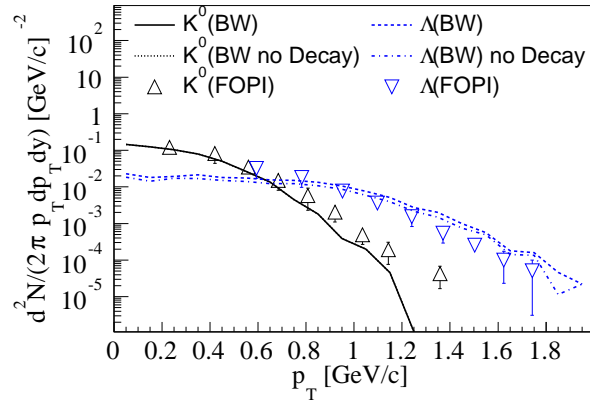


FIG. 2: (Color online) The transverse momentum p_T distribution of K^0 and Λ at mid-rapidity in Ni + Ni central collisions at $\sqrt{s_{NN}} \approx 2.6$ GeV. Lines represent the model calculations with $T_{kin} = 30$ MeV, $\rho_0 = 0.6$, $T_{ch} = 49$ MeV and $\mu_B = 815$ MeV; Symbols are data from the FOPI collaboration [14].

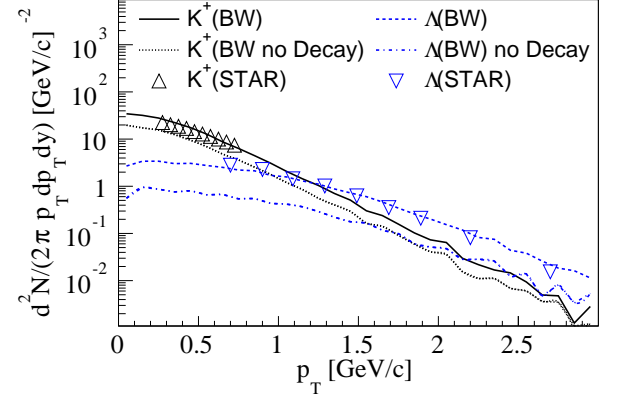


FIG. 3: (Color online) The transverse momentum p_T distribution of K^+ and Λ at mid-rapidity in Au + Au central collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Lines represent the model calculations with $T_{kin} = 105$ MeV, $\rho_0 = 0.7$, $T_{ch} = 156$ MeV and $\mu_B = 70$ MeV; Symbols are data from the RHIC-STAR collaboration [16, 17].

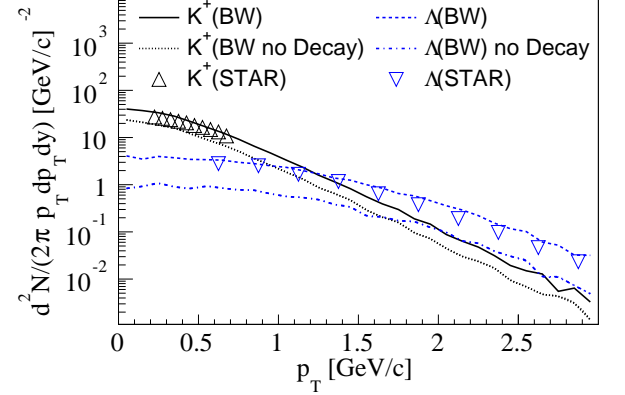


FIG. 4: (Color online) The transverse momentum p_T distribution of K^+ and Λ at mid-rapidity in Au + Au central collisions at $\sqrt{s_{NN}} = 200$ GeV. Lines represent the model calculations with $T_{kin} = 91$ MeV, $\rho_0 = 0.8$, $T_{ch} = 156$ MeV and $\mu_B = 20$ MeV; Symbols are data from the RHIC-STAR collaboration [18, 19].

for different particles species, the ratio between the different particles will give the chemical freeze-out temperature and baryon (strangeness) chemical potentials. In this paper, a blast wave model with chemical equilibrium model is employed to calculate the transverse momentum (p_T) spectra of Kaon and Λ in nucleus - nucleus collisions at ultra-relativistic energy $\sqrt{s_{NN}}$ from 2.6 GeV to 2.76 TeV corresponding to the FOPI, RHIC and LHC energy range.

Figure 2 shows the transverse momentum distribution of K^0 and Λ by the blast wave model compared with the data from FOPI collaboration [14] in Ni + Ni collisions at $\sqrt{s_{NN}} \approx 2.6$ GeV. Our results can describe the data well. The chemical temperature T_{ch} and the baryon chemical potential μ_B used in this calculation is similar to the ones

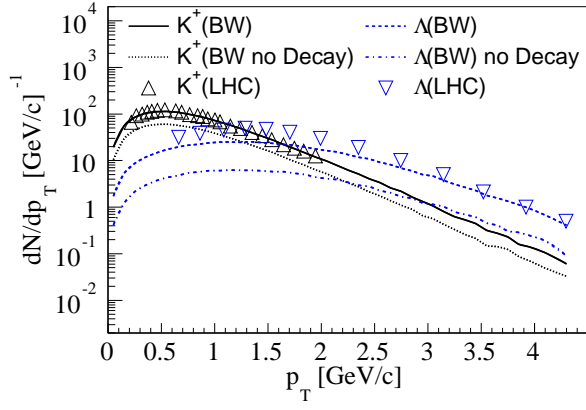


FIG. 5: (Color online) The transverse momentum p_T distribution of K^+ and Λ at mid-rapidity in Pb + Pb central collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Lines represent the model calculations with $T_{kin} = 99$ MeV, $\rho_0 = 1$, $T_{ch} = 160$ MeV and $\mu_B = 10$ MeV; Experimental data are taken from Refs. [20, 21].

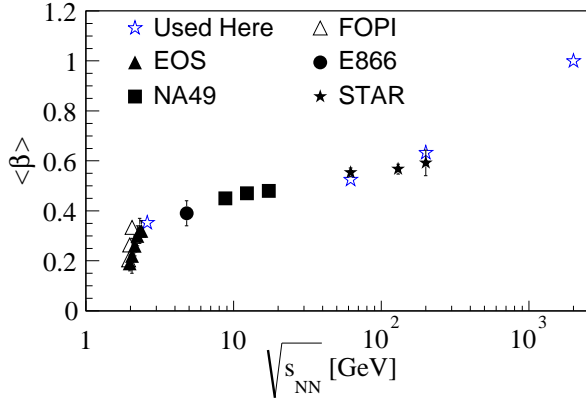


FIG. 6: (Color online) The radial flow parameters as a function of centre of mass energy $\sqrt{s_{NN}}$; data are taken from the RHIC-STAR collaboration [18, 19].

applied in reference [37]. And the kinetic freeze-out parameters of temperature T_{kin} and radial flow ρ_0 is chosen from experimental results with compilation in the reference [16]. The production of Kaon and Λ here is near the Λ threshold, thus it can be a reference in Lanzhou-Cooling Storage Ring (CSR) facility and High Intensity Accelerator Facility (HIAF) in the near future. Figure 3 and 4 present the transverse momentum distributions of K^+ and Λ at mid-rapidity in Au + Au central collisions at $\sqrt{s_{NN}} = 62.4$ GeV and 200 GeV, respectively. The chemical and kinetic freeze-out parameters are extracted from data as in Refs. [16, 35, 36]. And for LHC energy the chemical freeze-out parameters and kinetic freeze-out temperatures were already discussed in our previous study [24] and figure 5 presents the p_T distribution of K^+ and Λ in Pb+Pb central collisions at $\sqrt{s_{NN}} \simeq 2.76$ TeV. Our calculated results are in good agreement with the p_T distribution from experiment. From figure 2, 3, 4, and 5, it can be found that the transverse momentum dis-

tributions of Λ is harder than those of Kaon. The slope (effective temperature) of the momentum distribution is related to both the radial flow parameter $\langle\beta\rangle$ and the mass of particles (m_0), i.e. $T_{eff} = T_{kin} + \frac{1}{2}m_0\langle\beta\rangle^2$ [41–43]. The radial flow will push the heavier particle to high transverse momentum, therefore the stiffer spectrum emerges for Λ in contrast with Kaon.

As discussed above the collective properties of the hot and dense matter created in ultra-relativistic heavy-ion collisions at freeze-out stage can be calculated through equation (5). Figure 6 shows the radial flow parameter $\langle\beta\rangle$ as a function of centre of mass energy $\sqrt{s_{NN}}$. It shows an increasing trend of the radial flow with the increasing of centre of mass energy $\sqrt{s_{NN}}$. Namely the expanding velocity of the collision system in radial direction is larger at higher energy. From figure 6 the radial flow used in this calculation is consistent with those extracted from the experimental results [16]. It implies that these parameters are also valid for strangeness hadrons.

The resonance production rate is high in nucleus-nucleus collisions at relativistic energy. The hadrons decayed from resonances will pollute the p_T distribution of hadrons produced in the collision [16]. However, it is difficult to measure the effect precisely in experiment due to the wide species of resonance. This can be done in model calculation, though. In our previous work [24] this effect for π , K and p is discussed in details in the LHC energy range. We show the results for strangeness hadron in different energy from figure 2, 3, 4 and 5 in this paper. In this calculation, Kaon's and Λ 's resonances are all included. The kaons (decayed from resonances) are mainly from $K^*(892)$, $\phi(1020)$ and other heavy resonances which their masses are heavier than that of 2 Kaons, and Λ 's (decayed from resonance) are mainly from Σ 's and Ξ 's resonances. From Eq.(4) and the mass of those particles mentioned above, one can estimate that the production rate from resonance decay of Λ s will be more than that of Kaons. And Table I summarises our estimation for this effect. The percent of $K^+(\Lambda)$ from resonance decay to total $K^+(\Lambda)$ is increased with the increasing of centre of mass energy $\sqrt{s_{NN}}$. The percentage for K^+ is higher than that for Λ . And the effect from resonance decay to K^+ and Λ is more significant at RHIC and LHC energy than the ones at low beam energy.

IV. SUMMARY

The blast wave model with a chemical equilibrium model is employed to calculate the production of Kaon and Λ in nucleus-nucleus collisions at relativistic energy. The baryon chemical potential μ_B and chemical freeze-out temperature T_{ch} are consistent with those extracted from experiments [16] and used in other model calculations [37]. The kinetic freeze-out properties are also discussed such as kinetic freeze-out temperature T_{kin} and radial flow parameter ρ_0 . These kinetic freeze-out parameters are in good agreement with the ones from exper-

TABLE I: Percent of K^+ and Λ from resonance decay in total K^+ and Λ vs. centre of mass energy $\sqrt{s_{NN}}$.

$\sqrt{s_{NN}}$ (GeV)	2.6	62	200	2000
$K^+(\text{decayed})/K^+(\text{total})[\%]$	0.2	44.4	44.6	46.9
$\Lambda(\text{decayed})/\Lambda(\text{total})[\%]$	19.5	73.8	74.1	74.9

imental results and are found to be valid for strangeness hadrons (Kaon and Λ). And the resonance decay effect on strangeness production is also studied in details in this paper. In summary, the beam energy dependence of Kaon and Λ production can be a good probe to study the properties of the dense matter created in ultra-relativistic heavy-ion collisions. Our results shed light on the beam energy scan at RHIC and the academic activity related to strangeness production at Lanzhou-CSR facility.

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